Towards Extraction of $\pi^+ p$ and $\pi^+\pi^+$ cross-sections from Charge Exchange Processes at the LHC.

R.A. Ryutin, V.A. Petrov, A.E. Sobol

Institute for High Energy Physics *142 281* Protvino, Russia

Abstract

We study the possibilities to analyse the data on leading neutrons production at first LHC runs. These data could be used to extract from it π^+p and $\pi^+\pi^+$ cross-sections. In this note we estimate relative contributions of π, ρ and a_2 reggeons to charge exchanges and discuss related problems of measurements.

1 Introduction

In recent papers [1],[2] we pushed forward (and discussed) the idea of using the Zero Degree Calorimeters [3], ZDCs, designed for different uses at several of the LHC collaborations, to extract the total and elastic cross-sections of the $\pi^+ p$ and $\pi^+\pi^+$ scattering processes. Actually, this could allow the use of the LHC as a πp and $\pi\pi$ collider at effective c.m.s. energies about 1-5 TeV. For further motivation and technical details we refer the reader to Refs. [1],[2].

In this paper we concentrate on quite a serious problem of the ρ- and a_2-exchanges in the processes $p+p \to n+X$ and $p+p \to n+X+n$ which compete with the π^+-exchange and are to be considered in detail.

2 The basic model of charge exchange processes and extraction of $\pi^+\ p$ and $\pi^+\ \pi^+$ cross-sections.

We consider processes presented in Fig. 1. Signal processes of Single (SπE) and double (DπE) pion exchanges are depicted in Fig. 1 a), e). In the previous articles [1],[2] we estimated contributions to the background of reactions depicted in Fig. 1c)d)g)h) and also minimum bias (MB) and single dissociation (SD) with forward neutrons production. In the present work we give calculations of events from Fig. 1 b), f), which are called single (SRE) and double (DRE) reggeon exchanges. In the DRE contributions of $\pi\ \rho$ and $\pi\ a_2$ collisions dominate over $\rho\ \rho$, $\rho\ a_2$ and $a_2\ a_2$ processes.

Details of calculations can be found in [1],[2]. Here we show only basic issues. As an approximation for π exchanges we use the formulas shown graphically in Fig. 2. If we take into account absorptive corrections, which were calculated in the Regge-eikonal model [4], these formulas can be rewritten as

$$\frac{d\sigma_{\text{S}\pi\text{E}}}{d\xi dt} = F_0(\xi, t) S(s/s_0, \xi, t)\ \sigma_{\pi^+ p}(\xi s), \tag{1}$$
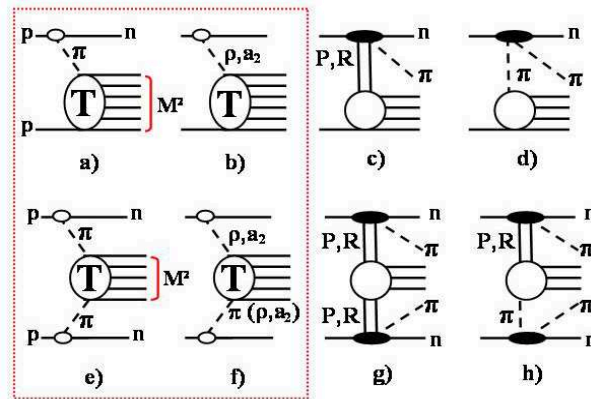
Figure 1: *Signal and background processes: a) SπE signal; b) SRE background; c)d) Double Dissociative (DD) background; e) DπE signal; f) DRE background (contributions from $\pi\ \rho$ and $\pi\ a_2$ collisions dominate); g)h) Central Diffractive (CD) background.*
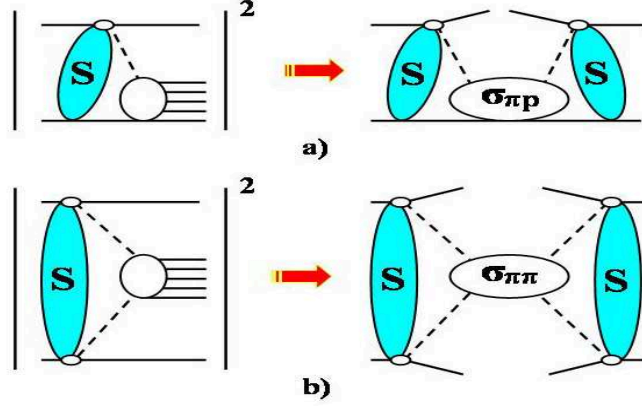
Figure 2: *Amplitudes squared and cross-sections of the processes: a)* $p + p \to n + X$ *(SπE), b)* $p + p \to n + X + n$ *(DπE). S represents soft rescattering corrections.*

$$\frac{d\sigma_{\text{D}\pi\text{E}}}{d\xi_1 d\xi_2 dt_1 dt_2} = F_0(\xi_1, t_1) F_0(\xi_2, t_2) S_2(s/s_0, \{\xi_i\}, \{t_i\}) \, \sigma_{\pi^+\pi^+}(\xi_1\xi_2 s), \tag{2}$$

$$F_0(\xi, t) = \frac{G^2_{\pi^+ pn}}{16\pi^2} \frac{-t}{(t - m_\pi^2)^2} e^{2bt} \xi^{1 - 2\alpha_\pi(t)}, \tag{3}$$

where the pion trajectory is $\alpha_\pi(t) = \alpha'_\pi(t - m_\pi^2)$. The slope $\alpha'_\pi \simeq 0.9$ GeV^{-2}, $\xi = 1 - x_L$, where x_L is the fraction of the initial proton's longitudinal momentum carried by the neutron, and $G^2_{\pi^0 pp}/(4\pi) = G^2_{\pi^+ pn}/(8\pi) = 13.75$ [5]. From recent data [6],[7], we expect $b \simeq 0.3$ GeV^{-2}. We are interested in the kinematical range 0.01 GeV$^2 < |t_i| < 0.5$ GeV^2, $\xi_i < 0.4$, where formulaes (1),(2) dominate according to [8] and [9].

Rescattering corrections S and S_2 are calculated in [1],[2]. Behaviour of $S \, t/m_\pi^2$ is shown in the Fig. 3. It is clear from the figure that $|S| \sim 1$ at $|t| \sim m_\pi^2$ (the situation is similar for S_2), which is an argument for the possible model-independent extraction of πp and $\pi\pi$ cross-sections by the use of (1) and (2) [2].
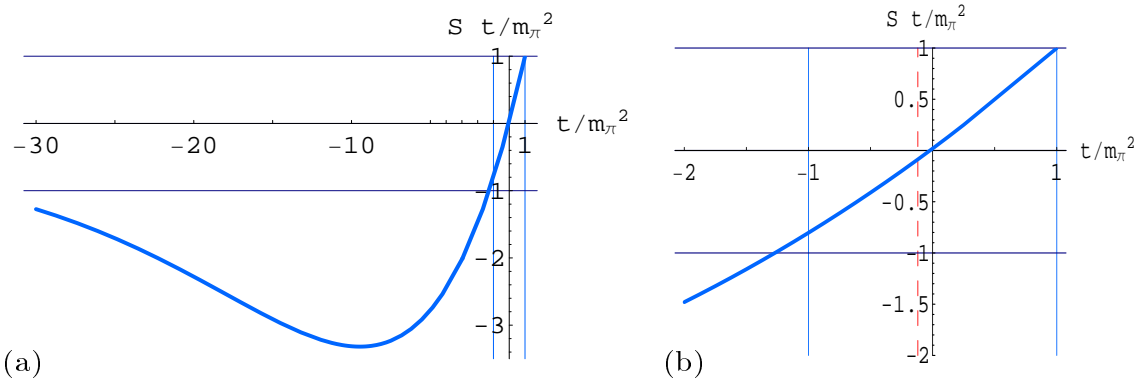

Figure 3: *Function $S(\xi, t) \, t/m_\pi^2$ versus t/m_π^2 at fixed $\xi = 0.05$. The boundary of the physical region $t_0 = -m_p^2 \xi^2/(1 - \xi)$ is represented by vertical dashed line in b).*

3

The present design of detectors does not allow t measuremets, it gives only restrictions $|t| <\sim 1$ GeV^2 at 7 TeV ($|t| < 0.3$ GeV^2 at 0.9 TeV). If to assume a weak enough t-dependence of πp and $\pi\pi$ cross-sections, i.e.

$$\sigma_{\pi_{virt}^+ p}(s; \{m_p^2, t\}) \simeq \sigma_{\pi^+ p}(s; \{m_p^2, m_\pi^2\}), \ \sigma_{\pi_{virt}^+ \pi_{virt}^+}(s; \{t_1, t_2\})| \simeq \sigma_{\pi^+ \pi^+}(s; \{m_\pi^2, m_\pi^2\}), \quad (4)$$

then we could hope to extract these cross-sections (though, with big errors) by the following procedure:

$$\tilde{S}(\xi) = \int_{t_{min}}^{t_{max}} dt \ S(s/s_0, \xi, t) F_0(\xi, t),$$

$$\sigma_{\pi^+ p}(\xi s) = \frac{\frac{d\sigma_{S\pi E}}{d\xi}}{\tilde{S}(s, \xi)}, \ \xi \simeq \frac{M_{\pi p}^2}{s}, \tag{5}$$

$$\tilde{S}_2(\xi_0) = \int_{t_{min}}^{t_{max}} dt_1 dt_2 \int_{-y_0}^{y_0} dy \ S_2(s/s_0, \{\xi_0 e^{\pm y}\}, \{t_i\}) F_0(\xi_0 e^y, t_1) F_0(\xi_0 e^{-y}, t_2),$$

$$\sigma_{\pi^+ \pi^+}(\xi_0^2 s) = \frac{\frac{d\sigma_{D\pi E}}{d\xi_0}}{\tilde{S}_2(s, \xi_0)}, \ \xi_0 = \frac{M_{\pi\pi}}{\sqrt{s}}, \ y_0 = \ln \frac{\xi_{max}\sqrt{s}}{M_{\pi\pi}}. \tag{6}$$

Functions $\tilde{S}_2(s, \xi_0)$ and $\tilde{S}(s, \xi)$ are depicted in Fig. 4. To suppress theoretical errors of $\tilde{S}$ and $\tilde{S}_2$ we have to measure total and elastic pp rates at energies greater than 2 TeV, since all the models for absorptive corrections are normalized to pp cross-sections. At present we can estimate the theoretical error to be less than 20% at ~ 10 TeV for this method from predicted values of total pp cross-sections in the most popular models [2].
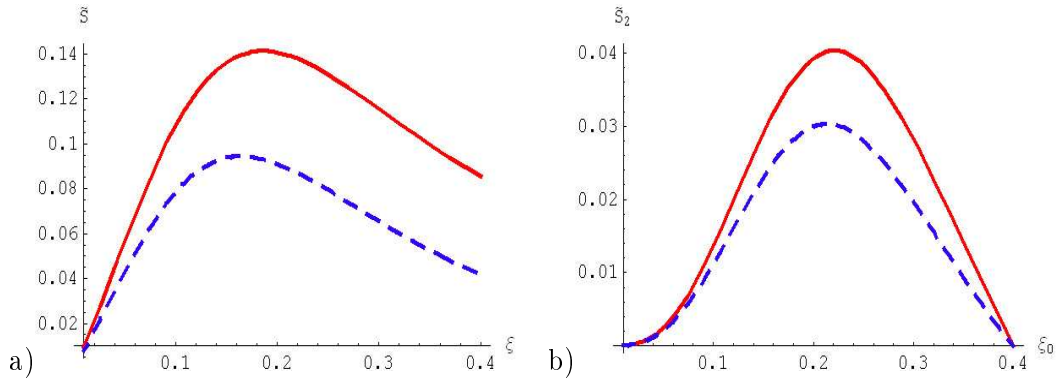

Figure 4: *Rescattering corrections integrated with formfactors for* $\sqrt{s} = 0.9$ *TeV (solid) and* $\sqrt{s} = 7$ *TeV (dashed): a)* $\tilde{S}(s, \xi)$; *b)* $\tilde{S}_2(s, \xi_0)$.

For ρ and a_2 contributions we can write formulaes similar to (1), (2):

$$\frac{d\sigma_{\text{SRE}}}{d\xi dt} = F_R(\xi, t) S_R(s/s_0, \xi, t) \, \sigma_{R^+ p}(\xi s), \tag{7}$$

$$\frac{d\sigma_{\text{DR}\pi\text{E}}}{d\xi_1 d\xi_2 dt_1 dt_2} = F_{R\pi}(\xi_1, \xi_2, t_1, t_2) S_{R,2}(s/s_0, \{\xi_i\}, \{t_i\}) \, \sigma_{R^+ \pi^+}(\xi_1 \xi_2 s), \tag{8}$$

$$F_R(\xi, t) = \frac{|\eta_R|^2 \tilde{G}_{R^+ pn}^2}{16\pi^2} e^{2b_R t} \xi^{1-2\alpha_R(t)} \left(1 + \kappa_R^2 \frac{\vec{q}^{\,2}}{4m_p^2}\right), \tag{9}$$

$$F_{R\pi}(\{\xi_i\}, \{t_i\}) = F_0(1) F_R(2) + F_0(2) F_R(1) + 2\sqrt{\frac{F_0(1) F_0(2) F_R(1) F_R(2)}{t_1 t_2 (1-\xi_1)(1-\xi_2)}}$$

$$\times \; \frac{\left(m_p \xi_1 + \vec{q}_1^{\,2} \frac{\kappa_R}{2m_p}\right)\left(m_p \xi_2 + \vec{q}_2^{\,2} \frac{\kappa_R}{2m_p}\right)}{\left(1 + \vec{q}_1^{\,2} \frac{\kappa_R^2}{4m_p^2}\right)\left(1 + \vec{q}_2^{\,2} \frac{\kappa_R^2}{4m_p^2}\right)}, \tag{10}$$

$$F_{0,R}(i) = F_{0,R}(\xi_i, t_i), \; \vec{q}_i^{\,2} \simeq -t_i(1-\xi_i) - m_p^2 \xi_i^2. \tag{11}$$

Here $\kappa_R = 8$ is the ratio of spin-flip to nonflip amplitude, $\alpha_R(t) \simeq 0.5 + 0.9t$ and parameters for ρ, a_2 mesons are [10]

$$\eta_\rho = -\imath + 1, \; \eta_{a_2} = \imath + 1, \tag{12}$$

$$b_\rho = 2 \text{ GeV}^{-2}, \; b_{a_2} = 1 \text{ GeV}^{-2}, \tag{13}$$

$$\frac{\tilde{G}_{\rho^+ pn}^2}{8\pi} = 0.18 \text{ GeV}^{-2}, \; \frac{\tilde{G}_{a_2^+ pn}^2}{8\pi} = 0.405 \text{ GeV}^{-2}. \tag{14}$$

Rescattering corrections S_R and $S_{R,2}$ are calculated by the method used in [1],[2]. Basic assumptions in our calculations are:

- $\rho\,\rho$, $\rho\,a_2$ and $a_2\,a_2$ contributions are small;

- interference terms of the type $T_{\text{S}\pi\text{E}}^* T_{\text{SRE}}$, $T_{\text{DR}\pi\text{E}}^* T_{\text{DR}'\pi\text{E}}$ are small [7], R, R$' = \pi$, ρ, a_2, $R \neq R'$, where T are amplitudes of the corresponding processes;

- approximate relations $\sigma_{R^+ p} \simeq \sigma_{\pi^+ p}$, $\sigma_{R^+ \pi^+} \simeq \sigma_{\pi^+ \pi^+}$ [7].

3 Relative contributions of π, ρ and a_2 exchanges to charge exchanges

Let us consider meson exchange contributions as a source of additional backgrounds for SπE and DπE. In Figs. 5 and 6 you can see contributions of pion and reggeon (sum of ρ and a_2) exchanges to single (CE) and double (DCE) charge exchange proceses. Here we use the kinematical variable r which is equal to the transverse distance from the beam and directly related to the pseudorapidity $r = L/\text{sh}(\eta)$. $L = 14000$ cm is the longitudinal distance from the interaction point to the detector. The best situation is observed at

$\sqrt{s} = 900$ GeV. Since the geometrical acceptance of the detector is $r \leq 5$ cm it cuts off reggeon background almost at all for the CE (Fig. 5b) and the significant part for the DCE (Fig. 5d). At 7 TeV the situation is not so good for DCE even if we peform a cut $r \leq 1$ cm (see Fig. 6d). It is difficult to separate different reggeon contributions from DCE in this case.
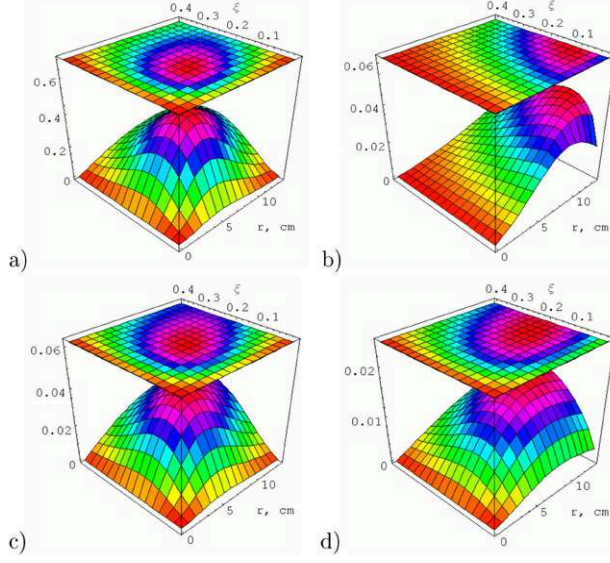

Figure 5: *Cross-sections $\frac{d\sigma}{d\xi dr}$ in $mb \cdot cm^{-1}$ at $\sqrt{s} = 0.9$ TeV for: a) $S\pi E$; b) $S\rho E + Sa_2 E$; c) $D\pi E$; d) $D\rho\pi E + Da_2\pi E$.*
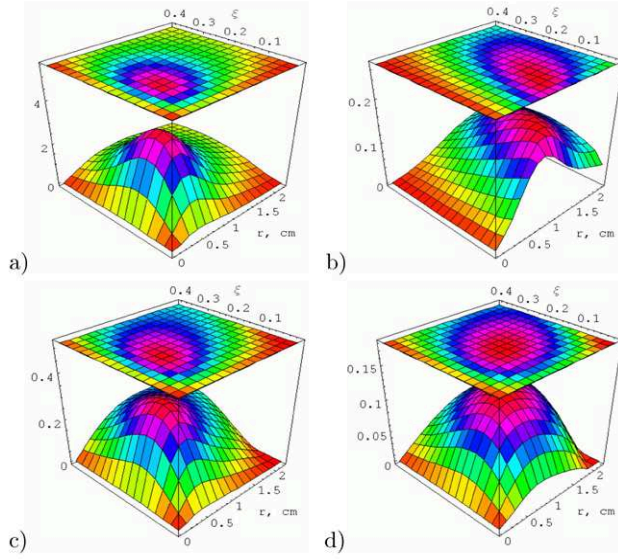

Figure 6: *Cross-sections $\frac{d\sigma}{d\xi dr}$ in $mb \cdot cm^{-1}$ at $\sqrt{s} = 7$ TeV for: a) $S\pi E$; b) $S\rho E + Sa_2 E$; c) $D\pi E$; d) $D\rho\pi E + Da_2\pi E$.*
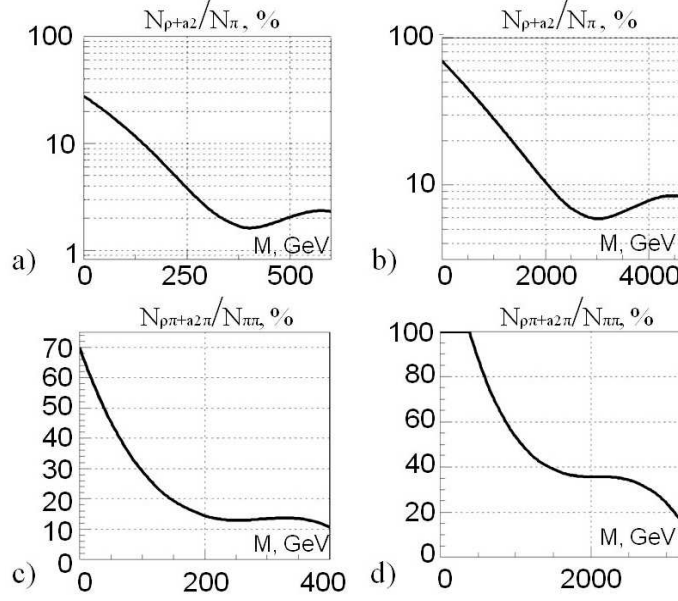
Figure 7: *Ratios of reggeon exchange events to pion exchange events in the ZDC acceptance versus the invariant mass of reggeon-proton (reggeon-reggeon) systems: a) $(N_{S\rho E}+N_{Sa_2E})/N_{S\pi E}$, $\sqrt{s} = 900$ GeV; b) $(N_{S\rho E} + N_{Sa_2E})/N_{S\pi E}$, $\sqrt{s} = 7$ TeV; c) $(N_{D\rho\pi E} + N_{Da_2\pi E})/N_{D\pi E}$, $\sqrt{s} = 900$ GeV; d) $(N_{D\rho\pi E} + N_{Da_2\pi E})/N_{D\pi E}$, $\sqrt{s} = 7$ TeV. Results for different models are similar.*

Table 1: *Relative contributions of reggeons to CE and DCE in the ZDC acceptance.*

$\sqrt{s}$, TeV		0.9	7
$(\sigma_{S\rho E} + \sigma_{Sa_2E})/\sigma_{S\pi E}$, %		10.7	8.2
	$S\pi E$	27.8	86.6
ZDC acceptance, %	$S\rho E$	10.8	86.8
	Sa_2E	6.7	86.7
$\langle(N_{S\rho E} + N_{Sa_2E})/N_{S\pi E}\rangle$, %		3.0	8.2
$(\sigma_{D\rho\pi E} + \sigma_{Da_2\pi E})/\sigma_{D\pi\pi E}$, %		47.3	43.4
	$D\pi\pi E$	4.80	99.6
ZDC acceptance, %	$D\rho\pi E$	0.28	99.8
	$Da_2\pi E$	0.65	99.7
$\langle(N_{D\rho\pi E} + N_{Da_2\pi E})/N_{D\pi\pi E}\rangle$, %		19.3	43.4

Monte-carlo simulation shows relative contributions in detail (see Fig. 7 and Table 1). For CE situation is quiet encouraging, since reggeon background is less than 10% for large invariant masses (or ξ), and for DCE it can reach 19.3 (43.4)% at $\sqrt{s} = 0.9(7)$ TeV due to similar distributions in r.

4   Conclusions

In this article we have considered the problems due to extra reggeon exchanges which arise when trying to extract $\pi^+ p$ and $\pi^+ \pi^+$ cross-sections from the data on leading neutrons at the LHC. After the estimation of reggeon exchange contributions to the background

we can conclude that at present time we have some chances to extract total $\pi^+ p$ cross-sections from the first LHC data at 900 GeV (7 TeV) but with rather big errors (about 20-30%). With the data on $p\ p$ total and elastic cross-sections at 7 TeV and higher theoretical errors can be reduced significantly.

At present our preliminary analysis shows that the 900 GeV data are too poor to come to some valuable results. This is the reason that detectors like ZDC need modernization to improve their performance for the reach of πp and $\pi\pi$ collisions at the LHC.

Acknowledgements

References

[1] V. Petrov, R. Ryutin and A. Sobol, *LHC as πp and $\pi\pi$ collider*, Eur. Phys. J. C **65** (2010) 637.

[2] A. Sobol, R. Ryutin, V. Petrov, M. Murray, *Elastic π^+p and $\pi^+\pi^+$ scattering at LHC*, Eur. Phys. J. C **69** (2010) 641.

[3] A.S. Ayan et. al., *ZDC Technical Design Report*, CMS-IN-2006/54.

[4] V. A. Petrov and A. V.Prokudin, *The first three Pomerons*, Eur.Phys.J. C **23** (2002) 135.

[5] V. Stoks, R. Timmermans and J.J. de Swart, *On the pion - nucleon coupling constant*, Phys. Rev. C **47** (1993) 512; R.A. Arndt, I.I. Strakovsky, R.L. Workman and M.M. Pavan, *Updated analysis of $\pi\,N$ elastic scattering data to 2.1-GeV: The Baryon spectrum*, Phys. Rev. C **52** (1995) 2120.

[6] ZEUS Collab., S Chekanov et al., *Leading neutron production in $e^+\ p$ collisions at HERA*, Nucl. Phys. B **637** (2002) 3.

[7] B.Z. Kopeliovich, B. Povh and I. Potashnikova, *Deep inelastic electroproduction of neutrons in the proton fragmentation region*, Z. Phys. C **73** (1996) 125.

[8] K.G. Boreskov, A.B. Kaidalov and L.A. Ponomarev, *Nucleon spectra in $p\ p$ collisions and the reggeized pi-meson exchange model*, Sov. J. Nucl. Phys. **19** (1974) 565.

[9] K.G. Boreskov, A.B. Kaidalov, V.I. Lisin, E.S. Nikolaevskii, L.A. Ponomarev, *Model of reggeized one pion exchange and reaction $p\ p\ \rightarrow\ p\ n\pi^+$*, Sov.J.Nucl.Phys. **15** (1972) 203.

[10] P.E. Volkovitsky, A.M. Lapidus, V.I. Lisin, K.A. Ter-Martirosian, *Experimental Data FIT in the Theory of Pomeron with $\alpha_{IP}(0) > 1$ and Some of Its Consequences*, Sov. J. Nucl. Phys. **24** (1976) 648.

a) $\dfrac{\sigma_{\pi p, tot}}{\sigma_{pp, tot}}$ $\sqrt{s}$, TeV

b) $\dfrac{\sigma_{el}}{\sigma_{tot}} \to \dfrac{pp}{\pi p}$ $\sqrt{s}$, TeV

c) σ_{el}/σ_{tot} $S^{1/2}$, GeV

a)   b)